AZUSA PLANT

STRUCTURAL MATERIALS DIVISION

INVESTIGATION OF STRESS-CORROSION CRACKING OF HIGH-STRENGTH ALLOYS

A Report To

FRANKFORD ARSENAL

Contract DA-04-495-ORD-3069

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AEROJET-GENERAL CORPORATION

AZUSA, CALIFORNIA

This is the twenty-third in a series of informal monthly progress reports submitted in partial fulfillment of Contract DA-04-495-ORD-3069. It constitutes the seventh monthly progress report for the one-year continuation of the original two-year program.

This report covers the period 1 April through 30 April 1963. It was written by R. B. Setterlund who was supervised by A. Rubin.

AEROJET-GENERAL CORPORATION

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NOTE: The information contained herein is regarded as preliminary and subject to further checking, verification, and analysis.

I. OBJECTIVES

The objectives of this program are outlined below:

A. Investigation of the stress-corrosion cracking characteristics of at least three new high-strength alloys of interest for rocket motor case applications. These alloys are 6Al-4V titanium, 18%-nickel maraging steel, and 20%-nickel maraging steel, in addition to limited testing of vacuum-melted 9Ni-4CO steel.

B. Study of the environmental parameters that could affect the rate and extent of stress-corrosion cracking.

C. Determination of the effect of material parameters (composition, strength level, welding, and microstructure) on stress-corrosion susceptibility.

D. Continuation of the evaluation of protective coatings and other techniques for preventing stress-corrosion cracking.

II. SUMMARY

Results obtained to date indicate that the 6Al-4V titanium alloy is immune to stress-corrosion cracking in the annealed, quenched and aged and as-welded conditions.

The 20%-nickel maraging steel is found to be highly susceptible to stress-corrosion cracking in the annealed-and-aged condition. Welding and aging the material causes it to become more susceptible; all failures occur in the heat-affected zone of the weld. When the alloy is cold-worked 50 or 75% before aging, the resistance to stress-corrosion cracking is greatly increased.

The 18%-nickel maraging steel was also found to be susceptible to stress-corrosion cracking. While the 18%-nickel grade was found to have a longer time-to-failure than the annealed-and-aged 20%-nickel steel in the distilled water,

II Summary (cont.)

salt water, seacoast air, trichloroethylene, and 140°F water-saturated air environments, it showed some failures in tap water, chromate solution and soluble oil solutions where the 20%-nickel grade was not affected. As with the 20%-nickel steel it was found that prior cold-working decreased the stress-corrosion cracking susceptibility.

Fifteen coating systems designed to prevent stress-corrosion cracking are under evaluation over H-11 steel, heat-treated to give high failure susceptibility. The most promising systems are the two inhibited epoxy and one pure vinyl system.

III. WORK PROGRESS

A. INTRODUCTION

Since the initiation of the original test program, two years ago, to investigate the stress-corrosion cracking characteristics of high-strength alloys, a number of new high-strength steels have been receiving increased attention for use in constructing rocket motor cases. The third-year test program is directed to the study of three of these new alloys, as well as of one titanium alloy presently being used for the same application.

The test environments, substantially the same as those evaluated in the original two-year investigation, are as follows: (1) distilled water; (2) tap water; (3) salt water; (4) sodium dichromate-inhibited water; (5) soluble oil-inhibited water; (6) air; (7) high humidity atmosphere; (8) trichloroethylene; (9) cosmoline; and (10) solid propellant. These are considered to be environments representative of those to which rocket motor cases would normally be exposed during fabrication, processing, and storage. One additional environment is included in the new program, that of sea-coast atmospheric exposure.

The test methods being used in this investigation employ bent-beam, U-bend, and center-notched specimens. Evaluation of results includes microstructural studies, using both standard metallographic and electron microscopic techniques, to attempt to associate the failure mechanism with specific microstructural characteristics of the materials.

III Work Progress, A (cont.)

An evaluation of protective coatings and surface treatments to prevent stress-corrosion cracking is also being conducted.

B. PROGRAM STATUS

During the period covered by this report, four more groups of bent-beam samples of maraging steels were placed in test. These are: Group I-4 on 9 April, Group I-2 on 15 April, Group H-W on 30 April, and Group I-W on 8 May. (These code numbers refer to Table 1 designations of processing condition,) These bent-beam samples are now in test in all environments except seacoast atmospheric exposure. Seacoast testing on these four groups of specimens will start on 20 May.

Center-notch testing of the maraging steels has been continued during the last monthly period. Also, evaluation of the mechanical properties of one heat of 9Ni-4Co vacuum cast alloy has been made (Code J-1 in Table 1); stress-corrosion testing of this material will start within the next month.

Chemical and mechanical properties of the four materials being evaluated in the program are shown in Tables 2 through 4.

Results of the bent-beam and center-notch tests run to date are shown in Tables 5 through 18. Microexaminations of bent-beam failures of welded-and-aged 20%-nickel maraging steel indicate that all failures occur in the weld heat-affected-zone. A section made of a failed specimen of welded 18%-nickel steel indicates that the failure occurs in the weldment. In both the 18%- and 20%-nickel steels failures of annealed samples are of an intergranular branching pattern as indicated in earlier reports. When either the 18%- or 20%-nickel steels were cold-worked before aging, it was found that its susceptibility to stress-corrosion cracking was reduced and, at the same time, the mode of cracking changed from intergranular to possible cracking along the slip planes. This effect was most clearly shown with the 20%-nickel grade of maraging steel. Photomicrographs of both of these types of failures were included in the last quarterly report.

The results of the coating evaluation program is shown in Table 19. Fifteen different coatings are under test in three environments: aerated 3% N Cl

III Work Progress, B (cont.)

solution, 140°F water-saturated air, and outdoor seacoast exposure. As can be seen in Table 19, no single coating has been able to prevent stress-corrosion cracking in all three environments completely. However, based on data accumulated to date, the best coatings, two inhibited-epoxy systems, 454-1-1 and 463-1-5 and pure vinyl Type 33, have significantly delayed failure of highly susceptible H-11 steel specimens and are considered to be very promising.

IV. FUTURE WORK

Work will continue along the guidelines of the master plan shown in Table 1. Both bent-beam and center-notched specimens will be tested to fulfill as much as possible of this schedule. Only the 9Ni-4Co alloy remains to be tested. This testing will be only exploratory due to the lateness of the delivery of the alloy.

Metallographic sections of selected cracked samples have been photographed and presented in the last quarterly report. In addition, photomicrographs will be made on cracked 18%- and 20%-nickel maraging steel welded samples.

Three samples were studied by means of the electron microscope, utilizing fracture replicas. Selected fractographs were presented in the last quarterly report. For the final report an additional set of fractographs are being prepared using a failed sample of annealed-and-aged 18%-nickel maraging steel.

V. BUDGET

The expenditure rate for the month of April was 272 hours, leaving 207 hours for the final two months of May and June.

Table 1

Report No. 10414-01-23

Alloy	Processing Condition (Titanium Content of Maraging Steel Shown)	Strength Level, 0.2% Offset Yield (psi)	Specimen Code	Number of Test Environments: Distilled Water	Tap Water	3% NaCl Solution	0.25% Sodium Dichromate Solution	4% Soluble Oil Solution	High Humidity	Trichloro-ethylene	Cosmoline	Solid Propellant	Ambient Air	Sea Coast Atmosphere	Total
6Al-4V titanium	Annealed	138,000	G-1	3*	3	3	3	3	3	3	3	3	-	3	30
	Quenched and Aged	163,000	G-2	3	3	3	3	3	3	3	3	3	-	3	30
	Welded	135,000	G-W	2	2	2	2	2	2	2	2	-	2	2	20
	Total			8	8	8	8	8	8	8	8	6	2	8	80
20%-Nickel Maraging Steel	Annealed and Aged	291,000	H-1	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW and Aged	321,000	H-2	3	3	3	3	3	3	3	3	3	3	3	33
	75% CW and Aged	298,300	H-3	3	3	3	3	3	3	3	3	3	3	3	33
	Welded and Aged	To be tested	H-W	3	3	3	3	3	3	3	3	3	3	3	33
	Total			12	12	12	12	12	12	12	12	12	12	12	132
18%-Nickel Maraging Steel	Annealed & Aged (0.62% Ti)	283,000	I-1	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.50% Ti)	302,400	I-2	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.62% Ti)	323,000	I-3	3	3	3	3	3	3	3	3	3	3	3	33
	Annealed & Aged (0.50% Ti)	249,900	I-4	3	3	3	3	3	3	3	3	3	3	3	33
	50% CW & Aged (0.40% Ti)	278,000	I-5	3	-	2	-	-	3	-	-	-	1	2	11
	Annealed & Aged (0.52% Ti)	255,400	I-6	3	-	2	-	-	3	-	-	-	2	3	13
	50% CW & Aged (0.52% Ti)	331,000	I-7	3	-	2	-	-	3	-	-	-	2	3	13
	Annealed & Aged (1.00% Ti)	323,200	I-8	3	-	2	-	-	3	-	-	-	1	2	11
	50% CW & Aged (1.00% Ti)	354,400	I-9	3	-	2	-	-	3	-	-	-	2	2	12
	Welded & Aged (0.50% Ti)	To be tested	I-W	3	3	3	3	3	3	3	3	3	3	3	33
	Total			30	15	23	15	15	30	15	15	15	23	27	225
9 Ni-4 Co Vacuum-Cast Alloy	Aged (0.25-0.30% C)	To be tested	J-1	3	3	3	3	3	3	3	3	3	3	3	33
	Aged (0.40-0.45% C)	To be tested	J-2	3	3	3	3	3	3	3	3	3	3	3	33
	Total			6	6	6	6	6	6	6	6	6	6	6	66
H-11 Steel (Coating Tests)	Application of Various Protective Coatings			-	-	37	-	-	29	-	-	-	-	26	92
	Total			56	41	86	41	41	85	41	41	39	43	79	595

*Number of replicate tests conducted.

TABLE 2

Supplier	Heat No.	Mill-Certified Analysis, % C	Mn	P	S	Si	Ni	Co	Mo	Al	Cb	Cr	Zr	Ti	Ca	B
Allegheny-Ludlum	W-24254	0.009	0.09	0.002	0.005	0.06	20.41	--	-	0.29	0.39	-	0.002	1.40	0.004	0.003
	W-24178	0.012	0.01	0.003	0.005	0.01	18.69	8.90	4.92	0.029	-	-	0.003	0.62	0.006	0.002
↓	477	0.018	0.002	0.006	0.004	0.024	18.29	9.10	4.95	0.089	-	-	<0.004	0.40	<0.0006	<0.003
	448	0.029	0.002	0.004	0.008	0.009	18.51	8.48	4.92	0.089	-	-	<0.004	0.52	<0.0006	<0.003
Allegheny-Ludlum	476	0.020	0.002	0.006	0.005	0.014	18.60	9.05	4.90	0.078	-	-	<0.004	1.00	<0.0006	<0.003
Republic Steel	3960502	0.020	0.08	0.007	0.006	0.15	18.48	7.00	4.84	0.21	-	0.10	0.035	0.50	Added	0.0036

Heat No.	Prior Condition	Aging Treatment	Table 1 Code No.	Transverse Mechanical Properties (Aerojet Tests) 0.2%-Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	% Elongation in 2 in.	Reduction in Area, %	Crack-Growth Energy (G_c), in.-lb/in.^{2}	R_c Hardness
W-24254	Annealed	none	-	128.5	170.7	7.5	53	-	34
↓	Annealed	-100°F +850°F 4 hr	H-1	291.3	302.2	3	17	58.3	54
	50% CW	none	-	184.0	201.6	5	50	-	39
	50% CW	850°F 4 hr	H-2	321.0	327.1	3	25	22.7	55.5
	75% CW	none	-	205.7	220.9	6	46	-	44
	75% CW	850°F 4 hr	H-3	298.3	308.8	2.5	13	15.7	55
↓	Welded	none	-	124.4	146.7	3.5	25	-	-
W-24254	Welded	-100°F +850°F 4 hr	H-W	245.0	252.0	1.5	5	-	-
W-24178	Annealed*	none	-	102.0	153.3	14.8	62	-	30.5
↓	Annealed*	900°F 3 hr	I-1	283.0	294.0	8	38	552.0	53.5
	50% CW	none	-	167.7	189.0	3.5	51	-	36.5
W-24178	50% CW	900°F 3 hr	I-3	323.8	328.4	1.5	28	220.0	55
477	50% CW	none	-	169.3	196.9	6.5	40	-	38.5
477	50% CW	900°F 3 hr	I-5	278.0	280.7	2	8	435.0	55.0
448	Annealed	none	-	105.3	150.3	10	45	-	30.5
↓	Annealed	900°F 3 hr	I-6	255.4	265.9	5	9	634.0	52
↓	50% CW	none	-	175.5	199.8	4.5	47.5	-	38
448	50% CW	900°F 3 hr	I-7	331.0	332.5	1.5	7	525.0	55
476	Annealed	none	-	128.3	174.7	5.5	48	-	36
↓	Annealed	900°F 3 hr	I-8	323.3	330.0	2.5	27	402.0	56
↓	50% CW	none	-	192.2	217.0	2.5	40	-	41
476	50% CW	900°F 3 hr	I-9	354.4	354.9	1	1.5	156.5	58
3960502	Annealed	none	-	119.5	143.5	7	55	-	29.5
↓	Annealed	900°F 3 hr	I-4	249.9	254.7	4	37	670.0	50.5
	50% CW	none	-	166.2	182.9	5.5	58.5	-	35.5
	50% CW	900°F 3 hr	I-2	302.5	308.1	4	26	321.0	52.5
↓	Welded	none	-	124.5	145.0	4.5	47	-	-
3960502	Welded	900°F 3 hr	I-W	236.6	242.0	2	20	-	-

*Material received in the 50% cold-worked condition and annealed at 1500°F in the laboratory.

TABLE 3

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES
OF 6Al-4V TITANIUM

	Chemical Analysis,* %								
	C	Al	V	O_2	N_2	H_2	Ti	Fe	Other
Aerojet analysis	0.3	6.1	4.1	0.083	0.014	80 ppm	Bal	0.16	0.18

	Mechanical Properties (Transverse)			
	Yield Strength (0.2% Offset) psi	Ultimate Strength psi	Elongation %	R_c Hardness
Annealed				
Mill report	131,900	141,400	12	33.5
Aerojet test	138,000	143,800	14	34
Notched tensile strength**	--	128,500	-	-
1675°F 1 hour, W.Q. aged 900°F 8 hour				
Aerojet test	162,700	176,800	7	38.5
Notched tensile strength	--	132,000	-	-
Welded				
Aerojet test	131,500***	135,200	9.5	33.0

* Titanium Metals Corporation HT 4141.

** Using as-fatigue-cracked sample of Figure 3.

*** Tensile failures in parent metal.

TABLE 4

CHEMICAL ANALYSIS AND MECHANICAL PROPERTIES OF
9Ni-4Co VACUUM CAST ALLOY

Mill Certified Chemical Analysis*

C	Mn	P	S	Si	Co	Ni	Cr	Mo	V
0.30	0.23	0.006	0.007	0.02	4.10	8.65	0.43	0.35	0.10

Mechanical Properties (Transverse) Aerojet Tests

Condition	Yield Strength (0.2% Offset) ksi	Ultimate Tensile Strength ksi	Elongation %	% Reduction of Area	Rc Hardness
(Austenitized 1550°F in argon - oil quenched 2 hours double temper at temperatures shown)					
400°F	190.3	230.3	8	52	48
600°F	184.6	203.0	7	54	43
800°F	172.4	186.7	9	59	41
1000°F	176.7	187.1	11	60	40.5

*Republic Heat 3950924

TABLE 5

BENT BEAM TESTS, STRESS-CORROSION* CRACKING IN AERATED DISTILLED WATER

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	3/3	11	10.2-18
↓	50% CW & Aged	H-2	321.0	1/3	330	330-NF1600
↓	75% CW & Aged	H-3	293.3	3/3	2918	1284-3450
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	3/3	83	23-200
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	3/3	68	60-85
↓	↓	I-6	255.4	0/3	-	NF1200
↓	↓	I-1	283.0	3/3	34.5	20.5-46.5
↓	Annealed & Aged	I-8	323.2	3/3	24	20-27.5
↓	50% CW & Aged	I-5	278.0	0/3	-	NF1200
18%-Ni Maraging Steel	↓	I-2	302.5	0/3	-	NF840
↓	↓	I-7	331.0	0/3	-	NF1200
↓	↓	I-3	323.0	4/4	625	440-988
↓	50% CW & Aged	I-9	354.4	1/3	668	668-NF1200
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	3/3	343	310-360

Notes:

* All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

** Refers to code letter in master schedule, Table 1.

*** Indicates no failures of three samples exposed.

TABLE 6

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN AERATED TAP WATER*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	0/3	-	NF3100
	50% CW & Aged	H-2	321.0	1/3	330	330-NF1600
	75% CW & Aged	H-3	298.3	2/3	2200	1284-NF3100
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	3/3	5.2	3.3-6.5
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	0/3	-	NF980
	Annealed & Aged	I-1	283.0	2/3	350	325-NF2000
	50% CW & Aged	I-2	302.5	0/3	-	NF840
	50% CW & Aged	I-3	323.0	0/3	-	NF2000
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/3	-	NF400

Notes:

*All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

**Refers to code letter in the master schedule, Table 1.

***Indicates no failures of three samples exposed.

TABLE 7

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN AERATED SALT WATER*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	3/3	7.3	6-8.5
↓	50% CW & Aged	H-2	321.0	0/3	-	NF1600
↓	75% CW & Aged	H-3	298.3	0/3	-	NF3100
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	3/3	0.8	0.75-0.85
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	3/3	430	140-700
↓	↓	I-6	255.4	0/2	-	NF1200
↓	↓	I-1	283.0	3/3	51.5	19-100
↓	Annealed & Aged	I-8	323.2	2/2	6.5	6-7
↓	50% CW & Aged	I-5	278.0	0/2	-	NF1200
↓	↓	I-2	302.5	0/3	-	NF840
↓	↓	I-7	331.0	0/2	-	NF1200
↓	↓	I-3	323.0	2/3	1290	1000-NF2000
↓	50% CW & Aged	I-9	254.4	2/2	20	20-20
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	4/4	121	115-139

Notes:

* All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

** Refers to code letter in master schedule, Table 1.

*** Indicated no failures of three samples exposed.

TABLE 8

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN AERATED 0.25% SODIUM DICHROMATE*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	1/3	1.0	1-NF3100
↓	50% CW & Aged	H-2	321.0	0/3	-	NF1600
↓	75% CW & Aged	H-3	298.3	0/3	-	NF3100
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	0/3	-	NF500
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	0/3	-	NF980
↓	Annealed & Aged	I-1	283.0	3/3	117	100-150
↓	50% CW & Aged	I-2	302.5	0/3	-	NF840
↓	50% CW & Aged	I-3	323.0	0/3	-	NF2000
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/3	-	NF400

Notes:

*All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicated no failures of three samples exposed.

TABLE 9

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN 4% SOLUBLE OIL SOLUTION*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-Welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	0/2	-	NF2000
20%-Ni Maraging Steel	50% CW & Aged	H-2	321.0	0/3	-	NF1600
20%-Ni Maraging Steel	75% CW & Aged	H-3	298.8	0/3	-	NF2000
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	0/3	-	NF500
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	0/3	-	NF980
	Annealed & Aged	I-1	283.0	3/3	417	400-450
	50% CW & Aged	I-2	302.5	0/3	-	NF840
	50% CW & Aged	I-3	323.0	0/3	-	NF2000
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/3	-	NF400

Notes:

*All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of three samples exposed.

TABLE 10

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN 140°F MOISTURE-SATURATED AIR*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	3/3	100	22-174
↓	50% CW & Aged	H-2	321.0	1/3	1410	1410-NF1600
↓	75% CW & Aged	H-3	298.3	3/3	1200	1080-1860
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	3/3	10	1-14
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	3/3	370	170-475
↓	↓	I-6	255.4	3/3	280	212-362
↓	↓	I-1	283.0	3/3	21	20.5-21.5
↓	Annealed & Aged	I-8	323.2	3/3	56.5	25.5-72
↓	50% CW & Aged	I-5	278.0	0/3	-	NF1200
↓	↓	I-2	302.5	2/3	360	340-NF840
↓	↓	I-7	331.0	0/3	-	NF1200
↓	↓	I-3	323.0	3/3	260	245-290
↓	50% CW & Aged	I-9	354.4	3/3	833	560-1010
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	3/3	131	115-139

Notes:

* All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

** Refers to code letter in master schedule, Table 1.

*** Indicates no failures of three samples exposed.

TABLE 11

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN TRICHLOROETHYLENE IMMERSION*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Failure Time, hours Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1150
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1150
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF1150
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	3/3	742	550-960
↓	50% CW & Aged	H-2	321.0	0/3	-	NF1150
↓	75% CW & Aged	H-3	293.3	0/3	-	NF1150
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	3/3	48	40-64
18%-Ni Maraging Steel	Annealed & Aged	I-1	283.0	2/3	610	550-NF1150
↓	50% CW & Aged	I-2	302.5	0/3	-	NF480
↓	50% CW & Aged	I-3	323.0	0/3	-	NF1150
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/3	-	NF400

Notes:

*All samples stressed to give maximum outer fiber stress of 75% of 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of three samples exposed.

TABLE 12

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN COSMOLINE IMMERSION*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1700
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1700
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-11	291.3	0/3	-	NF2000
↓	50% CW & Aged	H-2	321.0	0/3	-	NF1000
↓	75% CW & Aged	H-3	293.3	0/3	-	NF2000
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	0/0	-	-
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	0/3	-	NF980
↓	Annealed & Aged	I-1	283.0	0/3	-	NF2000
↓	50% CW & Aged	I-3	323.0	0/3	-	NF2000
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/0	-	-

Notes:

*All samples stressed to give maximum outer fiber stress of 75% of 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of three samples exposed.

TABLE 13

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN LABORATORY AIR*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/0	-	-
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/0	-	-
6Al-4V Titanium	As-welded	G-W	135.0	0/2***	-	NF750
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	0/3	-	NF3100
	50% CW & Aged	H-2	321.0	0/2	-	NF1600
	75% CW & Aged	H-3	293.3	0/3	-	NF3100
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	0/3	-	NF170
18%-Ni Maraging Steel	Annealed & Aged	I-4	249.9	0/0	-	-
		I-6	255.4	0/2	-	NF1200
		I-1	283.0	0/3	--	NF2000
	Annealed & Aged	I-8	323.2	0/1	-	NF1200
	50% CW & Aged	I-5	278.0	0/1	-	NF1200
		I-2	302.5	0/0	-	-
		I-7	331.0	0/2	-	NF1200
		I-3	323.0	0/3	-	NF2000
	50% CW & Aged	I-9	354.4	0/2	-	NF1200
18%-Ni Maraging Steel	Welded & Aged	I-W	336.6	0/3	-	NF400

Notes:

*All samples stressed to give a maximum outer fiber stress of 75% of the 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of two samples exposed.

TABLE 14

BENT BEAM TESTS, STRESS-CORROSION CRACKING IN SEACOAST ATMOSPHERIC EXPOSURE*

Material	Variable	Code No.**	Yield Strength ksi	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	138.0	0/3***	-	NF1400
6Al-4V Titanium	Quenched & Aged	G-2	163.0	0/3	-	NF1400
6Al-4V Titanium	As-welded	G-W	135.0	0/2	-	NF1400
20%-Ni Maraging Steel	Annealed & Aged	H-1	291.3	3/3	140	116-188
↓	50% CW & Aged	H-2	321.0	3/3	1034	800-1150
↓	75% CW & Aged	H-3	293.3	3/3	1000	860-1150
20%-Ni Maraging Steel	Welded & Aged	H-W	245.0	0/0	-	-
18%-Ni Maraging Steel	Annealed & Aged	I-6	255.4	0/2	-	NF1400
↓	Annealed & Aged	I-1	283.0	6/6	380	312-450
↓	Annealed & Aged	I-8	323.2	2/2	700	350-1050
↓	50% CW & Aged	I-5	278.0	0/2	-	NF1400
↓	↓	I-2	302.5	0/0	-	-
↓	↓	I-7	331.0	0/2	-	NF1400
↓	↓	I-3	323.0	0/3	-	NF1400
↓	50% CW & Aged	I-9	354.4	0/2	-	NF1400
18%-Ni Maraging Steel	Welded & Aged	I-W	236.6	0/0	-	-

Notes:

*All samples stressed to give a maximum outer fiber stress of 75% of 0.2% offset yield strength.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of three samples exposed.

TABLE 15

CENTER NOTCH TESTS, STRESS-CORROSION CRACKING IN
0.25% SODIUM DICHROMATE

Material	Variable	Code No.*	K_c ksi$\sqrt{in}$	Failed/ Tested	Failure Time, hours Mean	Failure Time, hours Range
6Al-4V Titanium	Annealed	G-1	85.0	0/2**	-	NF100
6Al-4V Titanium	Quenched & Aged	G-2	86.2	0/2	-	NF100
20%-Ni Maraging Steel	Annealed & Aged	H-1	39.3	0/2	-	NF200
20%-Ni Maraging Steel	50% CW & Aged	H-2	24.5	0/0	-	-
20%-Ni Maraging Steel	75% CW & Aged	H-3	20.5	0/2	-	NF100
18%-Ni Maraging Steel	Annealed & Aged	I-4	133.0	0/1	-	NF100
↓	Annealed & Aged	I-1	121.0	1/1	67.9	-
↓	Annealed & Aged	I-8	103.8	1/1	37.7	-
↓	50% CW & Aged	I-5	107.2	0/1	-	NF200
↓	↓	I-2	92.2	0/0	-	-
↓	↓	I-7	119.0	0/2	-	NF100
18%-Ni Maraging Steel	50% CW & Aged	I-3	76.4	1/1	33.2	-

Notes:

*All samples given direct load of 75% of K_c.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of two samples tested.

TABLE 16

CENTER NOTCH TESTS, STRESS-CORROSION CRACKING IN 3% SODIUM CHLORIDE SOLUTION*

Material	Variable	Code No.**	K_c ksi$\sqrt{\text{in}}$	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	85.0	0/2***	-	NF100
6Al-4V Titanium	Quenched & Aged	G-2	86.2	0/2	-	NF100
20%-Ni Maraging Steel	Annealed & Aged	H-1	39.3****	1/1	4.2	-
↓	↓	H-1	39.3	2/2	7.2	6.6-7.8
		H-1	39.3*****	1/1	8.2	-
	Annealed & Aged	H-1	39.3******	1/1	12.7	-
↓	50% CW & Aged	H-2	24.5	2/2	14.0	8.20
20%-Ni Maraging Steel	75% CW & Aged	H-3	20.5	2/2	40.2	34.4-46
18%-Ni Maraging Steel	Annealed & Aged	I-4	133.0****	1/1	7.8	-
↓	↓	I-4	133.0	2/2	12.3	9.5-15.2
		I-4	133.0*****	1/1	64	-
		I-6	129.5	3/3	22	10-35
		I-1	121.0	2/2	20.6	18-23
	Annealed & Aged	I-8	103.2	2/2	8.8	8.3-9.3
	50% CW & Aged	I-5	107.2	2/2	13.4	12.5-14.2
	↓	I-2	92.2	2/2	7.2	7.2-7.2
		I-7	119.0	3/3	9.9	4.4-12.9
↓	↓	I-3	76.4	2/2	5.9	5.0-6.9
18%-Ni Maraging Steel	50% CW & Aged	I-9	64.4	2/2	4.5	5.0-4.0

Notes:

* All samples given direct load of 75% of K_c except as noted.

** Refers to code letter in master schedule, Table 1.

*** Indicates no failures of two samples tested.

**** Tested at 83% of K_c.

***** Tested at 60% of K_c.

****** Tested at 27% of K_c.

TABLE 17

CENTER NOTCH TESTS, STRESS-CORROSION CRACKING IN DISTILLED WATER*

Material	Variable	Code No.*	K_c ksi$\sqrt{in}$	Failed/ Tested	Failure Time, hours Mean	Range
6Al-4V Titanium	Annealed	G-1	85.0	0/3**	-	NF100
6Al-4V Titanium	Quenched & Aged	G-2	86.2	0/3	-	NF100
20%-Ni Maraging Steel	Annealed & Aged	H-1	39.3	3/3	5.1	4.6-6.6
20%-Ni Maraging Steel	50% CW & Aged	H-2	24.5	0/0	-	-
20%-Ni Maraging Steel	75% CW & Aged	H-3	20.5	1/3	121	121-NF300
18%-Ni Maraging Steel	Annealed & Aged	I-4	133.0	0/0		
	Annealed & Aged	I-6	129.5	0/1	-	NF200
	Annealed & Aged	I-1	121.0	3/3	85.3	83-87
	50% CW & Aged	I-5	107.2	0/1	-	NF200
		I-2	92.2	2/2	17.1	16.6-17.6
		I-7	119.0	0/0	-	-
		I-3	76.4	2/2	13.2	12.6-13.8
18%-Ni Maraging Steel	50% CW & Aged	I-9	64.4	0/0	-	-

Notes:

*All samples given direct load of 75% of K_c.

**Refers to code letter in master schedule, Table 1.

***Indicates no failures of three samples tested.

TABLE 18

CENTER NOTCH TESTS, STRESS-CORROSION CRACKING IN 4% SOLUBLE OIL SOLUTION*

Material	Variable	Code No.**	K_c ksi$\sqrt{in}$	Failed/ Tested	Failure Time, hours Mean	Failure Time, hours Range
6Al-4V Titanium	Annealed	G-1	85.0	0/1***	-	NF100
6Al-4V Titanium	Quenched & Aged	G-2	86.2	0/1	-	NF100
20%-Ni Maraging Steel	Annealed & Aged	H-1	39.3	0/2	-	NF200
20%-Ni Maraging Steel	Annealed & Aged	H-2	24.5	0/0	-	-
20%-Ni Maraging Steel	75% CW & Aged	H-3	20.5	0/1	-	NF100
18%-Ni Maraging Steel	Annealed & Aged	I-4	133.0	0/1	-	NF100
↓	Annealed & Aged	I-1	121.0	0/0	-	-
↓	50% CW & Aged	I-2	92.2	0/0	-	-
18%-Ni Maraging Steel	50% CW & Aged	I-3	76.4	0/0	-	-

Notes:

*All samples given direct load of 75% of K_c.

**Refers to code letter in master schedule, Table 1.

***Indicates no failure of one sample tested.

TABLE 19

Surface Condition	Coating	Aerated 3% NaCl Solution			140°F Saturated Air			Seacoast Exposure		
		Failure Ratio*	Failure Time, hr		Failure Ratio*	Failure Time, hr		Failure Ratio*	Failure Time, hr	
			Mean	Range		Mean	Range		Mean	Range
Surface ground or sanded	None (control)	4/4	1.6	0.8-2.5	2/2	64	48-70	2/2	116	116-116
	Polyurethane	3/3**	149	144-168	6/6**	3500	2830-5500	1/2	250	250-NF 900
	Inhibited epoxy 454-1-1	0/2	-	NF 1200	3/3**	2720	2590-2850	0/2	-	NF 900
	Inhibited epoxy 463-1-5	0/3	-	NF 3100	3/3	656	400-976	0/2	-	NF 900
	Inhibited epoxy 463-4-8	3/3	550	525-578	3/3	845	289-1512	-	-	-
	Epoxy 463-1-5 over 454-1-1	0/4**	-	NF 5860	4/4**	4000	2590-4950	-	-	-
	Zinc silicate, Type 4	2/2	1.2	0.8-1.6	2/2	422	147-696	1/2	116	116-NF 900
	80% aluminum epoxy	2/2	1.00	100-100	2/2	30	16-45	2/2	660	550-780
	70% titanium epoxy	2/2	150	140-160	2/2	198	136-256	1/2	720	720-NF 900
Sand-blasted	None (control)	2/2	18.5	14-23	1/1	26.5	-	1/1	188	-
	Pure vinyl	0/2	-	NF 1500	1/2	670	670-NF 1500	0/2	-	NF 900
	Zinc silicate, Type 4	2/2	14	10-18	0/2	-	NF 1500	0/2	-	NF 900
	Epoxy over zinc silicate, Type 4	2/2	77	1.5-153	2/2	513	422-504	0/1	-	NF 900
	Inorganic zinc, Type 11	2/2	687	674-702	2/2	821	723-819	0/4	-	NF 900
	Epoxy 188 over inorganic zinc 11	2/2	54	42-56	0/2	-	NF 2160	-	-	-
	Organic zinc XL-4-245	2/2	214	27-400	2/2	766	742-790	-	-	-
	Modified vinyl system	2/2	550	520-583	2/2	640	435-850	1/2	450	450-NF 900

*Ratio of number failed to number exposed.

**Data taken from earlier work; samples not in current testing.